

Revisiting the QCD Corrections to the R-Parity Violating Processes $p\bar{p}/pp \rightarrow e\mu + X$

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Abstract

We present the theoretical predictions up to QCD next-to-leading order for the cross section of high-mass electron-muon pair production at the Tevatron and at the Large Hadron Collider(LHC), considering only the dominant contributions from the third-generation sneutrino. The dependence of the renormalization and factorization scales on the total cross section, and the effects on the K -factor due to the uncertainty of parton distribution function(PDF) are carefully investigated. By considering soft-gluon resummation effects to all orders in α_s of leading logarithm, we present the transverse momentum distributions of the final $e\mu$ pair.

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Observation of electron-muon resonance high invariant mass (Q) at hadron colliders could provide evidence of R-parity violating(RPV) interactions. The $e\mu$ pair productions at hadron colliders induced by RPV interactions at the leading order were investigated in Ref.[1]. In Ref.[2, 3, 4] the QCD next-to-leading order(NLO) corrections to resonant sneutrino production at hadron colliders were studied, while the QCD corrections to R -violating process $p\bar{p}/pp \rightarrow q\bar{q}, gg \rightarrow e\mu + X$ involving three generations of sneutrinos and squarks was discussed in Ref.[5]. Since there are increasing interests in searching for high-mass $e\mu$ resonance at hadron colliders [6], we revisit this topic to provide thorough theoretical prediction as a reference for experimental analysis. In this Letter only resonance contributions from the third-generation sneutrino are involved in high-mass $e\mu$ search under the single dominance assumption, [7] and the contributions from squark-exchanging diagrams are neglected by applying a high threshold cut (Q_0) on $e\mu$ invariant mass.[1, 5] The tree-level and the one-loop QCD NLO diagrams for sneutrino $e\mu$ resonance subprocess considering in our calculation are depicted in Figs.1 and 2, respectively.



Figure 1: Tree-level Feynman diagrams for subprocess $d\bar{d} \rightarrow e\mu$.

We adopt the dimensional regularization(DR) method and the modified minimal subtraction ($\overline{\text{MS}}$) scheme. After renormalization procedure, the virtual correction part of the cross section is UV-finite. The IR divergences from the one-loop diagrams will be cancelled by adding the soft real gluon/light-quark emission corrections by using the two cutoff phase space slicing method (TCPSS).[8] The remaining collinear divergences can be absorbed into the parton distribution functions(PDF).

We use the CTEQ6L parton distribution functions for the tree-level cross sections and CTEQ6.1M for the QCD NLO corrected ones.[9, 10] During the numerical calculation, we

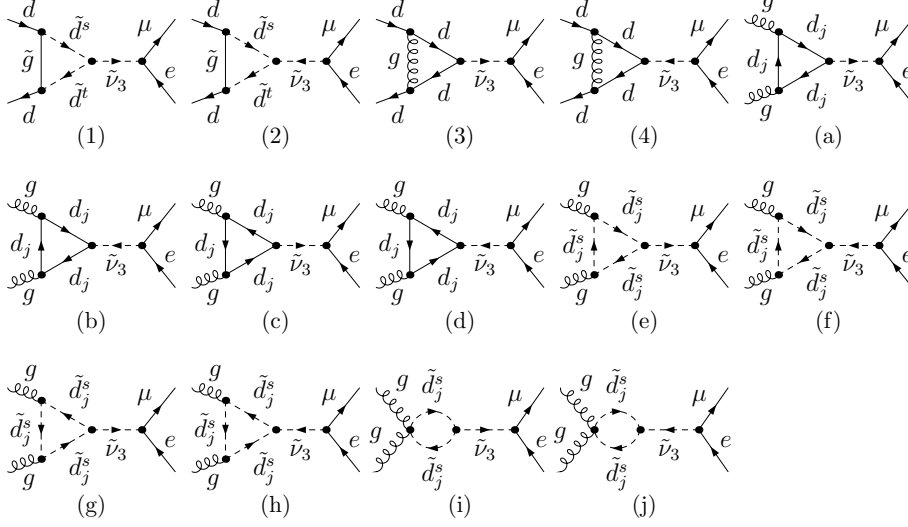


Figure 2: Fig.2. QCD one-loop diagrams (1)-(4) for subprocess $d\bar{d} \rightarrow e\mu$. QCD one-loop diagrams (a)-(j) for $gg \rightarrow e\mu$, where the superscripts $s, t (= 1, 2)$ represent two physical scalar quarks and the subscript $j (= 1, 2, 3)$ is for three generations.

also investigate the uncertainty induced by the factorization scale μ_f and the CTEQ6 PDF. We take 40 sets of CTEQ61.xx PDF's[10](set number goes from 201 to 240) to estimate the uncertainty induced by the PDF. Actually, in the precise calculation of the distributions of the transverse momentum(q_T) for the $e\mu$ pair, the quantitative comparison of q_T and Q is very crucial. When the q_T value is comparable with Q or larger, fixed order perturbation theory gives sufficiently accurate results. However, when $q_T \ll Q$, large logarithmic terms, such as $[\alpha_s \ln(q_T/Q)]^n$, arise at fixed order perturbation calculations and need to be resummed. Therefore, we adopt the standard procedure[11] to resum the multiple soft gluon effects on q_T distribution.

The R-violating lagrangian relevant to present discussion is expressed as[12]

$$\begin{aligned}
\mathcal{L}_{\cancel{R}} = & \frac{1}{2} \lambda_{ijk} \cdot (\bar{\nu}_{Li}^c e_{Lj} \tilde{e}_{jL}^* + e_{Li} \bar{\nu}_{Lj}^c \tilde{e}_{Rk}^* + \nu_{Li} e_{Lj} \bar{e}_{Rk} - e_{Li} \tilde{\nu}_{Lj} \bar{e}_{Rk}) + \\
& \lambda'_{ijk} \cdot (\bar{\nu}_{Li}^c d_{Lj} \tilde{d}_{Rk}^* - e_{Ri}^c u_{Lj} \tilde{d}_{Rk}^* + \nu_{Li} \tilde{d}_{Lj} \bar{d}_{Rk} - e_{Li} \tilde{u}_{Lj} \bar{d}_{Rk} + \\
& \tilde{\nu}_{Li} d_{Lj} \bar{d}_{Rk} - \tilde{e}_{Li} u_{Lj} \bar{d}_{Rk}) + h.c.
\end{aligned} \tag{0.1}$$

where $i, j, k = 1, 2, 3$ are generation indices, the superscript c refers to charge conjugation, λ and λ' are dimensionless R-violating Yukawa couplings, and λ behaves as $\lambda_{ijk} = -\lambda_{jik}$.

In the numerical calculations, we take the RPV parameters λ and λ' to be real for simplicity with the values as: $\lambda_{312} = 0.062$, $\lambda_{321} = 0.070$, $\lambda'_{311} = 0.11$, which are under the experimental constraints presented in Ref.[7]. We set the factorization and the renormalization scales being equal and $\mu_f = \mu_r = m_{\tilde{\nu}}$. The invariant mass cut of the $e\mu$ pair is set to be $Q_0 = 50$ GeV. We apply the naive fixed-width scheme in the sneutrino propagator to avoid the possible resonant singularities(here we fix $\Gamma_{\tilde{\nu}} = 10$ GeV as demonstration). In principle, the value choice of the width of sneutrino has an influence on the cross section, but does not affect the K -factor. Since the sneutrino is non-colored supersymmetric particle, there is no problem with double counting in the QCD NLO calculation of the $d\bar{d} \rightarrow e\mu$ cross section. The gluino and squark masses are taken as $m_{\tilde{g}} = m_{\tilde{q}} = 1$ TeV, in order to decouple the interactions involving gluino and squarks and neglect the contributions of squark-exchange diagrams. We have verified that the total cross section involving the QCD NLO corrections is independent of the cutoffs δ_s and δ_c in adopting the TCPSS method. In the following calculation, we fix the soft cutoff as $\delta_s = 10^{-3}$ and collinear cutoff as $\delta_c = \delta_s/50$. The calculations are carried out at the Tevatron and the CERN LHC with $p\bar{p}$ colliding energy $\sqrt{s} = 1.96$ TeV and pp colliding energy $\sqrt{s} = 14$ TeV, respectively. Since the \overline{MS} scheme violates supersymmetry, the $q\tilde{q}\tilde{g}$ Yukawa coupling constant \hat{g}_s takes a finite shift at one-loop order as[13]: $\hat{g}_s = g_s \left[1 + \frac{\alpha_s}{8\pi} \left(\frac{4}{3}N_c - C_F\right)\right]$, with $N_c = 3$ and $C_F = 4/3$. We shall take this coupling strength shift between \hat{g}_s and g_s into account in our calculation.

In Fig.3(a) we depict the curves of the tree-level and QCD NLO corrected cross sections(σ^0 and σ^{QCD}) of the processes $p\bar{p}/pp \rightarrow e^+\mu^- + X$ versus the sneutrino mass $m_{\tilde{\nu}}$ at the Tevatron and the LHC. Their corresponding K -factors($K \equiv \frac{\sigma^{QCD}}{\sigma^0}$) as a function of $m_{\tilde{\nu}}$ are depicted in Fig.3(b). We can see that both the K -factor curves for the Tevatron and the LHC colliders in Fig.3(b) show the difference between the curve tendencies of K -factors for processes $p\bar{p}(pp) \rightarrow e\mu + X$ and $p\bar{p}(pp) \rightarrow \tilde{\nu} + X$. For the later process, both the calculations in Ref.[2] and our cross-check for confidence show that the K -factor curve for the Tevatron always goes down when $m_{\tilde{\nu}}$ varies from 200 GeV to 1 TeV, while the K -factor curve for the LHC goes up with the increment of $m_{\tilde{\nu}}$ from 100 GeV to 600 GeV. It manifests that the QCD NLO corrections

to high-mass $e\mu$ resonance production at both the Tevatron and the LHC cannot be adopted directly from those for the single $\tilde{\nu}$ production process as presented in Refs.[2, 4]. We can read out from Fig.3(b) that the K -factors vary in the ranges of [1.182, 1.643] at the Tevatron and [1.335, 1.614] at the LHC.

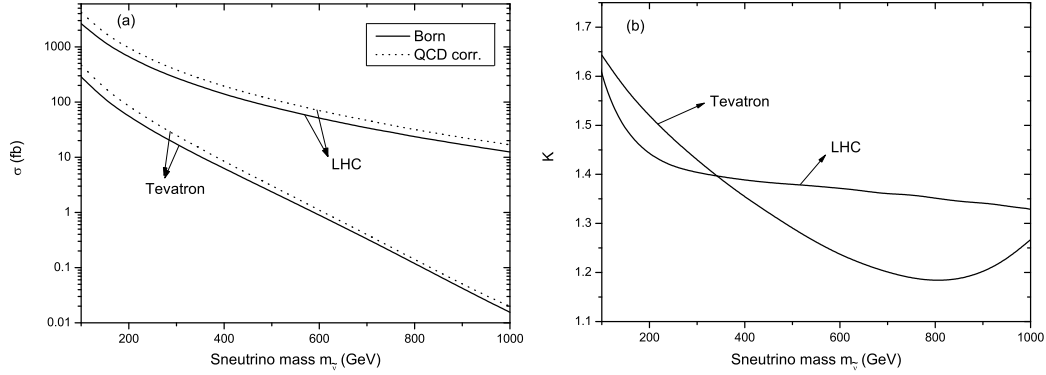


Figure 3: The tree-level and total QCD NLO corrected cross sections of the processes $p\bar{p}/pp \rightarrow e\mu + X$ at the Tevatron and the LHC as a function of the sneutrino mass $m_{\tilde{\nu}}$ are shown in Figure 3(a). Figure 3(b) shows the corresponding relations between the K -factors and the sneutrino mass $m_{\tilde{\nu}}$.

Figures 4(a) and 4(b) demonstrate the dependence of K -factor on the factorization scale $\mu_f/m_{\tilde{\nu}}$, when the sneutrino mass is set to be $m_{\tilde{\nu}} = 100, 250, 500$ GeV. From the two figures we can estimate the uncertainty of the QCD NLO correction induced by scale parameter μ_f . In Fig.4(a), we can read out that in the scale $\mu/m_{\tilde{\nu}}$ region of [0.5, 2] the K -factors at the Tevatron vary in the ranges of [1.639, 1.645], [1.446, 1.498] and [1.251, 1.328] corresponding to $m_{\tilde{\nu}} = 100, 250$ and 500 GeV respectively. Figure 4(b) shows that the K -factors at the LHC are in the ranges of [1.567, 1.668], [1.396, 1.434] and [1.362, 1.375] in the scale region of $\mu/m_{\tilde{\nu}} \in [0.5, 2]$ for $m_{\tilde{\nu}} = 100, 250$ and 500 GeV separately. From Figs.4(a) and 4(b) we can see the relative errors of K -factor induced by the factorization scale μ_f for $m_{\tilde{\nu}} = 100$ GeV, 250 GeV, 500 GeV in the scale region $\mu_f/m_{\tilde{\nu}} \in [0.5, 2]$ are 0.17%(3.1%), 1.8%(1.3%) and 3.0%(0.46%) at the Tevatron(LHC), respectively.

We investigate the uncertainty range due to the different CTEQ sets. In Table 1 we list the K -factor values obtained by using different CTEQ61.xx PDF sets, where the K -factor

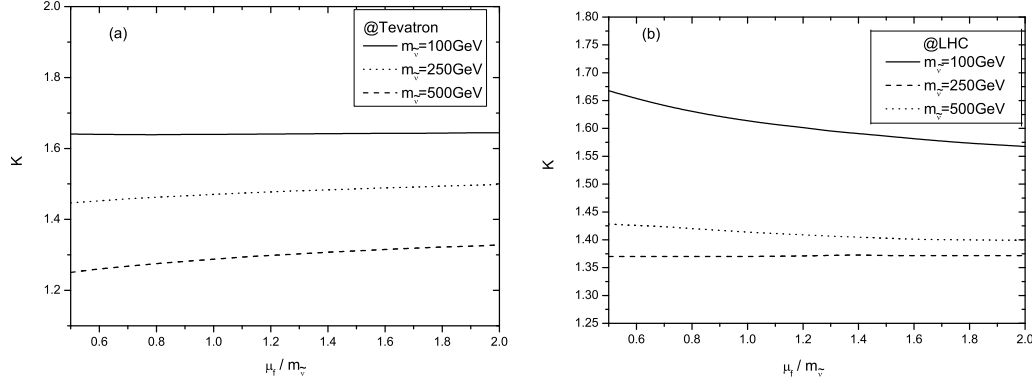


Figure 4: Dependence of K -factor on the factorization scale $\mu_f/m_{\tilde{\nu}}$. (a) at the Tevatron, (b) at the LHC.

obtained from the best fit CTEQ6.1M PDF is taken as the central value at sneutrino mass. From the data in Table 1 we find that the deviations of K -factor from the central value at the Tevatron are in the ranges of $[-0.053, 0.046]$, $[-0.055, 0.060]$, $[-0.073, 0.110]$ and the average values of absolute deviations are 0.014, 0.025, 0.042 for $m_{\tilde{\nu}} = 100, 250, 500$ GeV, respectively. The deviations of K -factor from the central value at the LHC are in the ranges of $[-0.057, 0.036]$, $[-0.044, 0.027]$, $[-0.057, 0.025]$, and the average values of absolute deviations are 0.018, 0.016, 0.019 for $m_{\tilde{\nu}} = 100, 250, 500$ GeV respectively. The relative errors of K -factor due to the PDF (defined as $\delta \equiv \frac{K_{max} - K_{min}}{K_{central}}$) for $m_{\tilde{\nu}} = 100$ GeV, 250 GeV, 500 GeV, are 6.0%(5.8%), 7.8%(5.0%) and 14.2%(5.9%) at the Tevatron(LHC), separately.

Considering soft-gluon resummation effects to all the orders in α_s of leading logarithm, we present the distributions of the differential cross sections ($d\sigma^{QCD}/dq_T$ and $d\sigma^{resum}/dp_T$) for the processes $p\bar{p}/pp \rightarrow e^+\mu^- + X$ versus the transverse momentum q_T with $m_{\tilde{\nu}} = 250$ GeV and 500 GeV in Figs.5(a) and 5(b), where q_T is defined as $q_T^2 = (\vec{p}_{eT} + \vec{p}_{\mu T})^2$. Figure 5(a) is for the process $p\bar{p} \rightarrow e\mu + X$ at the Tevatron and Figure 5(b) is for the process $pp \rightarrow e\mu + X$ at the LHC.

In summary, our numerical results demonstrate that the QCD corrections to single sneutrino production cannot directly be applied to the study of high-mass RPV $e\mu$ pair production. The K -factors of the processes $p\bar{p}/pp \rightarrow e\mu + X$ vary in the ranges of $[1.182, 1.643]$ and

CTEQ6	$m_{\tilde{\nu}} = 100 \text{ GeV}$		$m_{\tilde{\nu}} = 250 \text{ GeV}$		$m_{\tilde{\nu}} = 500 \text{ GeV}$	
	$K_{Tevatron}$	K_{LHC}	$K_{Tevatron}$	K_{LHC}	$K_{Tevatron}$	K_{LHC}
6.1M	1.643	1.614	1.471	1.418	1.290	1.379
201	1.610	1.576	1.458	1.379	1.285	1.335
202	1.672	1.631	1.492	1.432	1.293	1.386
203	1.643	1.582	1.505	1.397	1.339	1.356
204	1.638	1.629	1.444	1.419	1.239	1.366
205	1.632	1.607	1.505	1.400	1.373	1.349
206	1.648	1.601	1.448	1.411	1.217	1.374
207	1.590	1.591	1.416	1.376	1.233	1.320
208	1.689	1.616	1.531	1.432	1.345	1.403
209	1.625	1.565	1.454	1.381	1.268	1.348
210	1.657	1.651	1.499	1.433	1.313	1.375
211	1.640	1.620	1.479	1.411	1.306	1.358
212	1.644	1.591	1.473	1.403	1.275	1.359
213	1.645	1.608	1.480	1.410	1.304	1.366
214	1.639	1.601	1.473	1.403	1.275	1.355
215	1.638	1.596	1.468	1.396	1.227	1.353
216	1.634	1.602	1.479	1.407	1.351	1.367
217	1.642	1.604	1.473	1.414	1.357	1.377
218	1.629	1.596	1.474	1.391	1.233	1.336
219	1.684	1.635	1.502	1.444	1.320	1.400
220	1.601	1.577	1.451	1.373	1.268	1.324
221	1.634	1.618	1.482	1.416	1.292	1.362
222	1.638	1.601	1.478	1.396	1.308	1.351
223	1.666	1.623	1.495	1.427	1.319	1.384
224	1.655	1.620	1.485	1.420	1.280	1.375
225	1.668	1.619	1.511	1.425	1.338	1.390
226	1.651	1.620	1.479	1.421	1.285	1.370
227	1.634	1.592	1.512	1.400	1.378	1.366
228	1.645	1.590	1.527	1.393	1.392	1.351
229	1.643	1.618	1.485	1.413	1.324	1.362
230	1.630	1.557	1.496	1.380	1.306	1.350
231	1.646	1.583	1.488	1.397	1.296	1.360
232	1.652	1.620	1.485	1.423	1.298	1.374
233	1.665	1.627	1.492	1.431	1.298	1.380
234	1.666	1.627	1.490	1.430	1.294	1.388
235	1.648	1.595	1.526	1.403	1.396	1.363
236	1.639	1.588	1.529	1.399	1.401	1.354
237	1.637	1.586	1.526	1.398	1.400	1.359
238	1.647	1.595	1.529	1.399	1.395	1.360
239	1.655	1.606	1.504	1.409	1.339	1.372
240	1.656	1.603	1.513	1.406	1.351	1.366

Table 1: Full set of K -factor predictions for the CTEQ family of PDFs for $m_{\tilde{\nu}} = 100, 250, 500 \text{ GeV}$ at the Tevatron and the LHC.

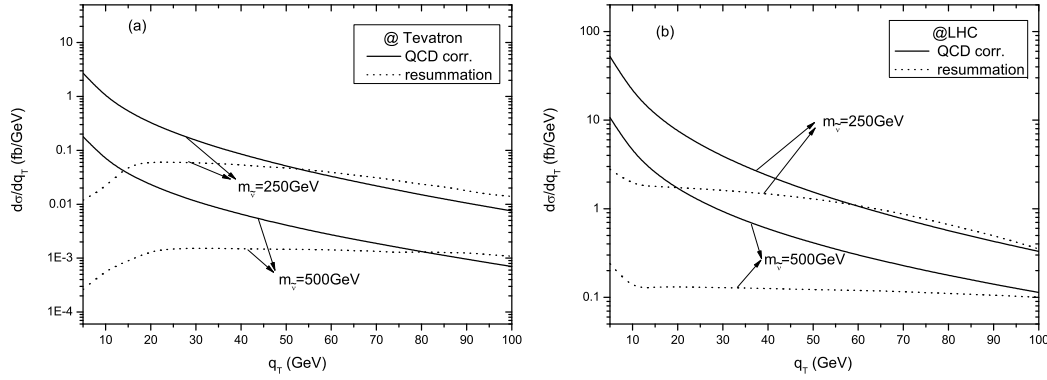


Figure 5: Distributions of the transverse momentum of final $e\mu$ -pair q_T , which is defined as $q_T^2 = (\vec{p}_{eT} + \vec{p}_{\mu T})^2$. (a) for the Tevatron, and (b) for the LHC.

[1.335, 1.614] at the Tevatron and the LHC separately, and the relative errors of K -factor are found to be less than 3%(3.1%) due to μ_f , and 14.2%(5.9%) due to PDF at the Tevatron(LHC) respectively in our investigating parameter space. We also present the distributions of the transverse momentum of final $e\mu$ -pair by resumming the logarithmically-enhanced terms for soft gluon as a reference for future experimental analysis.

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